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Measurement of the branching fraction of $B \to X_s\gamma$ and $\mathcal{A}_{CP}$ in $B \to X_{s+d}\gamma$ from Belle

L. Pesántez (for the Belle collaboration)

Physikalische Institut, Universtität Bonn
Nußallee 12, 53129 Bonn, Germany

Abstract

The transitions $b \to d\gamma$ and $b \to s\gamma$ are flavor-changing neutral currents, forbidden at tree level in the Standard Model (SM). These decays proceed via electroweak penguin loop diagrams and can be used to test the SM and new-physics effects. The SM gives very precise predictions when the decays are considered inclusively, for this reason it is important to perform studies where as many final states as possible are reconstructed or where the decay is considered fully inclusively, without explicitly reconstructing the B meson.

The large Belle data set of 711fb^{-1} recorded at the $\Upsilon(4S)$ resonance allows for precise measurements of radiative B-decays.

Keywords: Belle, radiative B decays, CP violation

1. Introduction

The decays $b \to d\gamma$ and $b \to s\gamma$ are flavor-changing neutral currents, which are forbidden at tree level in the Standard Model (SM). They proceed via penguin loop diagrams, where a top quark and a charged weak boson are exchanged. This makes these transitions sensitive to potential contributions of heavy non-SM particles present in the loop. In the operator product expansion (OPE) [1], the effective Hamiltonian that governs weak decays can be expressed as the sum of operators Q_i with corresponding Wilson coefficients C_i: $H_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_i V^i_{\text{CKM}} C_i(\mu) Q_i$. Non-SM contributions would modify the predicted values of the Wilson coefficients. For the decays $b \to d\gamma$ and $b \to s\gamma$, new physics effects can be calculated as modifications to the C_7 and C_8 coefficients [2]. The SM gives precise predictions for the inclusive decays, this makes it relevant to perform studies where as many final states as possible are reconstructed (semi-inclusive approach) or where the the B meson is not explicitly reconstructed (inclusive approach).

2. Experimental setup

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K^0_L mesons and to identify muons (KLM). The detector is described in detail elsewhere [3].

The Belle detector at the KEKB B-factory studies B-mesons produced in the reaction $e^+e^- \to \Upsilon(4S) \to B\bar{B}$. The studies presented here are performed using the complete Belle data set of 711fb^{-1}. Continuum processes ($e^+e^- \to q\bar{q}$, $q = u, d, s, c$) constitute a dominant background source in the B-factories, therefore a large effort is put into suppressing it. These events can be discriminated from $B\bar{B}$ since their decay products have a characteristic "jet-like" topology, in contrast to a

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more "spherical" topology from $B\bar{B}$. Topological variables such as thrust and sphericity are used for continuum suppression. Additionally, Belle uses a set of modified Fox-Wolfram moments [4]. The variables are consequently used to train a multivariate discriminant such as a Boosted Decision Tree (BDT) or Neural Network (NN) to achieve maximum discrimination.

3. $B \to X_s\gamma$ branching fraction

The $B \to X_s\gamma$ branching fraction is theoretically well understood, the branching fraction has been estimated up to next-to-next leading order [5], resulting in $\mathcal{B}(B \to X_s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$ for an energy $E_\gamma > 1.6$ GeV in the B-meson rest frame. The current experimental world average is $\mathcal{B}(B \to X_s\gamma) = (3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$, it is consistent with the SM estimation [6].

In the semi-inclusive approach (sum of exclusive final states) as many exclusive final states as possible are reconstructed in order to reduce the uncertainty from unmeasured modes. The B meson is reconstructed as the combination of a photon with energy 1.8 GeV $\leq E^*_\gamma \leq$ 3.4 GeV in the center of mass frame (CM), and one of 38 hadronic X_s final states. The X_s states consist of up to three kaons (K^+, K^0_S) with at most one K^0_S, up to four pions (π^+, π^0) with at most two π^0 and at most one η meson.

Peaking background arises from decays with similar final state to the signal such as $B \to D^{(*)}(K\pi\pi)\rho^+(\pi^+\pi^0)$, when one of the photons from a π^0 decay is highly energetic. These processes occur much more frequently than $b \to s\gamma$ and are therefore vetoed. The veto proceeds by reconstructing the D meson and rejecting events with a hadronic mass M_{X_s} close to the nominal D mass. The veto is applied for events with $M_{X_s} > 2.0$ GeV/c^2.

Continuum background is suppressed using a NN constructed with the modified Fox-Wolfram moments and ΔE, defined as $\Delta E = E^*_B - E^*_{\text{beam}}$ with E^*_B the CM energy of the reconstructed B and E^*_{beam}, the CM energy of the beams. The selection requirement on it maximizes the statistical significance in the region 2.2 GeV/c^2 $\leq M_{X_s} \leq$ 2.8 GeV/c^2.

The extraction of the signal proceeds as an unbinned maximum-likelihood fit to the beam constrain mass (M_{bc}) variable. It is defined as: $M_{\text{bc}} = \sqrt{E^{*2}_{\text{beam}} - p^{*2}_B}$ with p^*_B the CM momentum of the reconstructed B. M_{bc} peaks around the nominal B mass for signal events. The fit to M_{bc} in 19 M_{X_s} bins. Examples of the fit for the regions 1.4 GeV/c^2 $\leq M_{X_s} \leq$ 1.5 GeV/c^2 and 1.9 GeV/c^2 $\leq M_{X_s} \leq$ 2.0 GeV/c^2 are shown in Fig. 1.

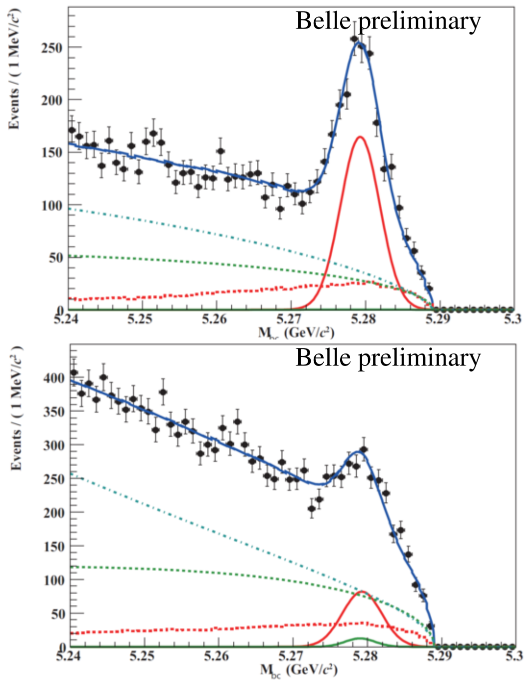

Figure 1: Result of the fit to M_{bc} in the bin 1.4 GeV/c^2 $\leq M_{X_s} \leq$ 1.5 GeV/c^2 (top plot) and 1.9 GeV/c^2 $\leq M_{X_s} \leq$ 2.0 GeV/c^2 (bottom plot) for the $B \to X_s\gamma$ analysis from Belle. The components are: signal (solid red), crossfeed (dashed red), peaking background (solid green), non-peaking $B\bar{B}$ background (dashed green) and continuum (dot-dashed cyan).

The measurement of the branching fraction is greatly influenced by the determination of the selection efficiency for each mode. The MC is calibrated to precisely model the efficiency found in data, the calibration is performed by tuning the Pythia parameters, which is used to model the X_s fragmentation. The dominant systematic uncertainties come from the calibration of MC efficiencies and the determination of the fit PDFs.

The measured branching fraction for $M_{X_s} <$ 2.8 GeV/c^2 and $E^*_\gamma >$ 1.8 GeV is $\mathcal{B}(B \to X_s\gamma) = (3.51 \pm 0.17 \pm 0.33) \times 10^{-4}$, where the first uncertainty is statistical and the second systematic. This result can be extrapolated to $E^*_\gamma >$ 1.6 GeV for a proper comparison with the theoretical estimate, yielding $\mathcal{B}(B \to X_s\gamma) = (3.74 \pm 0.18 \pm 0.35) \times 10^{-4}$. This result is in agreement with the SM prediction and with previous experimental results [6].

4. CP asymmetry in $B \to X_{s+d}\gamma$

The SM predicts non-vanishing CP asymmetries ($\mathcal{A}_{CP}$) for the $B \to X_d\gamma$ and $B \to X_s\gamma$ decays [7]. However, when both decays are considered inclusively the CP-violating contributions cancel due to CKM unitarity, and the theory errors cancel almost perfectly up to small corrections [2]. This precise SM prediction can serve as a clean test for new CP-violating phases. The asymmetry is defined as

$$\mathcal{A}_{CP} = \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)},$$

with $\Gamma(B \to f)$ being the decay rate into the final state $f = X_{s+d}\gamma$.

In this inclusively analysis, the signal B-meson is not reconstructed, but only a photon from its decay is selected. Photons with CM energy 1.7 GeV $\leq E^*_\gamma \leq$ 2.8 GeV are considered. The flavor of the signal B is determined by tagging the other B meson in the event by selecting a charged lepton ($e^\pm$ or $\mu^\pm$) originating from it. The charge of the lepton determines uniquely the flavor of the B mesons. There is a large number of photons arising from the decays $\pi^0(\eta) \to \gamma\gamma$, they are therefore vetoed. The continuum background is suppressed using a BDT. The BDT is constructed using 19 kinematic and topological variables.

Possible asymmetries in the selection or reconstruction procedures or in the background are carefully studied and quantified in order to avoid biasing the measurement of $\mathcal{A}_{CP}$. A possible charge asymmetry in the reconstruction of leptons is measured in a $B \to XJ/\psi(\ell^+\ell^-)$ sample with a "tag-and-probe" approach. The asymmetry is measured in 11 lepton momentum and 8 polar angular regions and independently for electrons and muons. The measured detection asymmetry is $\mathcal{A}_{\rm det} = (0.10 \pm 0.22) \times 10^{-2}$, this value is consistent with no asymmetry. A possible asymmetry in the $B\bar{B}$ background is measured in the sideband 1.4 GeV $\leq E^*_\gamma \leq$ 1.7 GeV. The raw asymmetry in data after continuum subtraction is measured as $\mathcal{A}_{\rm bkg} = \frac{N^+ - N^-}{N^+ + N^-}$, where N^+ and N^- correspond to the number of positive or negative tagged events. The measured asymmetry is $\mathcal{A}_{\rm bkg} = (-0.14 \pm 0.78) \times 10^{-2}$, also consistent with no asymmetry.

A wrong-tag factor ω arises in cases when the reconstructed lepton charge does not correspond to the flavor of the signal B-meson. The measured and true asymmetries are related as: $\mathcal{A}^{\rm true}_{CP} = \frac{1}{1-2\omega}\mathcal{A}^{\rm meas}_{CP}$. There are three effects contributing to this factor: oscillation neutral B mesons, secondary leptons and hadrons misreconstructed as leptons, being the first one of greater importance, its value was measured to be $\omega = 0.1413 \pm 0.0052$.

The $B \to X_{s+d}\gamma$ spectrum after background subtraction is shown in Fig. 2 and the asymmetry measurement for different photon energy thresholds in the range 1.7 GeV $\leq E^*_\gamma \leq$ 2.2 GeV is shown in Fig. 3. The asymmetry $\mathcal{A}_{CP}$ shows a stable behavior for the different energy thresholds and is consistent with the SM prediction. The measurement is statistically limited. For $E^*_\gamma > 2.1$ GeV we find $\mathcal{A}_{CP} = (2.2 \pm 4.0 \pm 0.8) \times 10^{-2}$. This measurement of $\mathcal{A}^{B \to X_{s+d}\gamma}$ is the most precise to date.

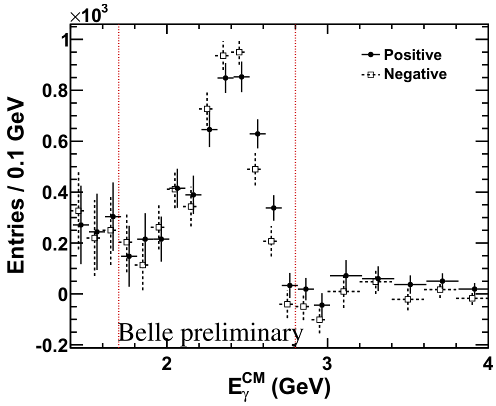

Figure 2: $B \to X_{s+d}\gamma$ spectrum after subtraction of background, for positive and negative leptons.

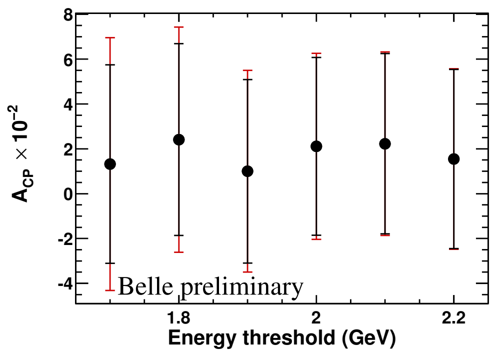

Figure 3: Measured $\mathcal{A}_{CP}$ for the different photon energy thresholds. The inner uncertainty bars are statistical and the outer include also systematic uncertainties.

5. Conclusions and outlook

The transitions $b \to d\gamma$ and $b \to s\gamma$ provide a rich set of observables that can be used to verify SM predictions and search for new physics effects. So far all results show good consistency with the SM. The measurement of the CP asymmetry in $B \to X_{s+d}\gamma$ decays is the most precise to date. It shows good agreement with the precise SM prediction and is stable with respect to the choice of the photon energy threshold in the range 1.7 GeV $\leq E^*_\gamma \leq$ 2.2 GeV. The latest Belle measurement of $\mathcal{B}(b \to s\gamma)$ uses a semi-inclusive approach, reconstructing 38 exclusive X_s final states. It is consistent with the SM and with previous experimental results.

The statistical precision is the limiting factor in the measurement of $\mathcal{A}_{CP}$ in $B \to X_{s+d}\gamma$ an is also an important contribution to the total uncertainty in the measurement $\mathcal{B}(b \to s\gamma)$. A better understanding of the X_s hadronization would greatly improve the precision on the branching fraction measurement. When considering these effects, it can be concluded that there is plenty of room for improvement when the large data sets from Belle II become available. Additionally, in these analyses both well established as well as new experimental techniques have been applied, the analyses at future super B-factory can greatly profit from the gathered experience.

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